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Aerodynamics of Engine-Airframe Interaction

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Final Report

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I. Preface

This document serves as a Final Report, summarizing the work performed from October 1, 1985 through October 31, 1988 under Grant NAG 2-373 from the NASA Ames Research Center. The Principal Investigator for the Grant was Professor David A. Caughey of the Sibley School of Mechanical and Aerospace Engineering of Cornell University; the Grant Technical Monitor was Dr. W. J. Chyu of the Aerodynamics Research Branch of the NASA Ames Research Center.

II. Accomplishments

Research was performed in the general area of Computational Aerodynamics, within two specific areas: (1) Solution adaptive procedures, and (2) Implicit multigrid methods for solving the Euler Equations of inviscid, compressible flows. The Grant has supported all or part of the Masters Thesis research of Gabriel Solomon and Ravi Iyer, as well as the Ph.D. Thesis research of Dr. Dun C. Liu and Yoram Yadlin.

Solution Adaptive Grids

The research on solution adaptive grids has concentrated upon developing the variational approach for the solution of inviscid aerodynamic problems. In particular, the formulation of a new, directional weighting, functional has been shown to have desirable properties. The scheme has been applied to compute the transonic flow past two-dimensional airfoils using the Euler equations of inviscid, compressible flow [P.1,

T.1]. Figure 1 shows the 'lift' and 'drag' plots of pressure distributions (pressure coefficient plotted versus x/c and y/c , respectively) for the symmetrical non-lifting flow past an NACA 0012 airfoil at 0.800 Mach number. This solution was computed on a smooth (i.e., non-adapted) grid, and differences can be seen between the solution and a reference solution computed on a much finer grid. The grid computed using the directional adaptation procedure is shown in Figure 2. Figure 3 shows the lift and drag pressure distributions for the solution computed on this adapted grid, again compared with the reference solution computed on a much finer mesh. The improvement in the agreement is clearly seen. Figures 4, 5, and 6 show similar results for a lifting case, corresponding to flow past the same airfoil at an angle of attack of 2.0 degrees and 0.80 Mach number. The adapted grid, shown in Figure 5 shows clustering toward the shock surface, but relatively little clustering in the direction along the shock surface, as desired. Again, comparison of Figure 6 with the smooth-grid results of Figure 4 shows significant improvement in the accuracy of the computed pressures. Further details regarding the method, and additional results, can be found in References [P.1, T.1].

The variational technique has also been used to generate solution-adaptive grids for the computation of the transonic cross-flow on delta wings using the potential approximation [T.2]. Figures 7 and 8 show a comparison of the solutions computed on smooth and adapted grids for one case. Contours of constant pressure are plotted for the Mach 2.0 flow past a flat elliptical-cone wing. The results using the adapted grid, shown in Figure 8, clearly resolve the shock more sharply than the smooth grid results of Figure 7. Two details of the adapted grid are shown in Figures 9 and 10; the clustering of grid lines near both the cross-flow shock (Figure 9) and the bow shock (Figure 10) are clearly seen.

Diagonal Implicit Multigrid Algorithm

A Diagonalized Implicit Multigrid Scheme has also been developed to solve the Euler equations, and has been applied to the calculation of transonic flows past airfoils [P.2 - P.5].

The scheme has also been extended to compute supersonic flows through and around two-dimensional inlets [P.6, T.3]. Figure 11 shows the grid system used for the calculation of the flow through an inlet studied earlier by NASA researchers (Pulliam and Chaussee). Figure 12 shows contours of constant pressure for the flow into the inlet at a freestream Mach number of 2.0. The bow wave, as well as many reflections of the wave systems within the inlet, are well captured. Figure 13 shows the distribution of pressure on the center-body surface, compared with the results of Pulliam and Chaussee. The results are generally in good agreement, with the results of the present method maintaining a much sharper representation of the reflected wave systems deep into the inlet. Finally, Figure 14 shows the convergence histories of calculations using different numbers of multigrid levels. The scheme using 3 levels of multigrid converges nearly three times as fast as the single level scheme.

The speed-up is not as impressive as that usually obtained for transonic flows, as the implicit solver marches the solution to its final steady state quite efficiently for flows which are entirely supersonic.

The Diagonal Implicit Multigrid method has also been applied to solve the Euler equations for three-dimensional problems, including the transonic flow past swept wings [P.7]. One such solution is shown in Figures 15 and 16. The upper and lower surface pressure distributions on the ONERA M-6 wing at 0.84 Mach number and 3.06 degrees angle of attack is shown in Figure 15; the contours of constant pressure on the wing upper surface, clearly showing the 'lambda' shock pattern, are shown in Figure 16. These results are computed on a "C"-grid containing $192 \times 32 \times 32$ mesh cells in the wraparound, wing-normal, and spanwise directions, respectively. The convergence history for this solution, computed on a single grid using the implicit solver, is shown in Figure 17. Similar convergence results are plotted for a calculation using five levels of multigrid are shown in Figure 18. Not only is the asymptotic rate of error reduction much improved, but the global features of the solution, including the force coefficients and the size of the supersonic pocket, have converged to within plottable accuracy in the equivalent of about 30 time steps. Current research is focussed upon the extension of the diagonal implicit multigrid scheme to block structured grids for three-dimensional problems [T.4]. Results have been obtained using the block-structured algorithm in two dimensions, including a parallel implementation on the multi-processing IBM 3090-600E computer [P.8].

III. Appendices

Copies of the abstracts of completed theses [T.1 - T.3] are attached as appendices to this report.

IV. Acknowledgements

The calculations supporting this grant have been performed at the Cornell National Supercomputer Facility, a resource of the Center for Theory and Simulation in Science and Engineering which receives major funding from the National Science Foundation and the IBM Corporation, with additional support from New York State and the Corporate Research Institute.

V. Publications

- P.1 *D. C. Liu and David A. Caughey, An Adaptive Grid Technique for Solution of the Euler Equations, AIAA Journal, Synoptic, in press.*

- P.2 *David A. Caughey, A Diagonal Implicit Multigrid Algorithm for Compressible Flow Calculations*, in **Advances in Computer Methods for Partial Differential Equations – VI**, R. Vichnevetsky and R. S. Stepleman, Eds., pp. 270-277, IMACS, New Brunswick, N.J., 1987.
- P.3 *David A. Caughey, An Efficient Implicit Multigrid Algorithm for the Euler Equations of Compressible Flow*, **Proc. of the International Conference of Fluid Mechanics** (Beijing 1987), pp. 392-397, Peking University Press, Beijing, China, July 1-4, 1987.
- P.4 *David A. Caughey and Eli Turkel, Effects of Numerical Dissipation on Finite-Volume Solutions to Compressible Flow Problems*, **AIAA Paper 88-0621**, 26th Aerospace Sciences Meeting, Reno, Nevada, January 11-14, 1988.
- P.5 *David A. Caughey, Diagonal Implicit Multigrid Algorithm for the Euler Equations*, **AIAA Journal**, Vol. 26, pp. 841-851, July, 1988.
- P.6 *Ravi Iyer and David A. Caughey, Diagonal Implicit Multigrid Calculation of Inlet Flow Fields*, **AIAA Journal**, Vol. 27, pp. 110-112, January 1989.
- P.7 *Yoram Yadlin and David A. Caughey, Diagonal Implicit Multigrid Solution of the Three-Dimensional Euler Equations*, **Proceedings of 11th International Conference on Numerical Methods in Fluid Dynamics**, Williamsburg, Virginia, June 27 - July 1, 1988.
- P.8 *Yoram Yadlin and David A. Caughey, Diagonal Implicit Multigrid Solution of the Euler Equations on Block Structured Grids*, accepted for presentation at the U. S. Army 7th Conference on Applied Mathematics and Computing, West Point, New York, June 1989.

VI. Theses

- T.1 *Dun C. Liu, Ph.D.*, August 1987, *An Adaptive Grid Technique for Solution of the Euler Equations*.
- T.2 *Gabriel Solomon, M.S.*, January 1988, *Solution Adaptive Mesh Calculations of Conical Potential Flows*.
- T.3 *Ravi Iyer, M.S.*, January 1988, *Diagonal Implicit Multigrid Solution of the Euler Equations for Two-Dimensional Inlets*.
- T.4 *Yoram Yadlin, Ph.D.*, June 1990 (expected), *Implicit Multigrid Solution of the Three-dimensional Euler Equations on Block-Structured Grids*.

AN ADAPTIVE GRID TECHNIQUE FOR SOLUTION OF THE EULER EQUATIONS

Dun Charles Liu, Ph.D.
Cornell University, 1987

In order to reduce errors associated with large solution gradients, under the constraint of a fixed number of grid points, it is desirable to have the grid clustered in regions of large gradient and loosely arranged in regions of small gradient. Such mesh systems cannot be constructed without knowledge of the behavior of the solution. As a result, the idea of solution adaptive grid generation has been one of the most important research areas in computational fluid dynamics in the past few years.

The grid equations in this work are formed from a linear combination of the Euler-Lagrange equations derived from functionals measuring smoothness, orthogonality and concentration (Brackbill and Saltzman [1982]). Since the weight function included in the concentration functional proposed by Brackbill and Saltzman [1982] is a scalar, no restriction in the direction of changing cell dimensions can be attained. A directional-concentration functional is here proposed to take this directional effect into consideration. Some salient features of the grid equations are explored by examining the existence of characteristic lines. The adaptive grid technique is applied to solve a finite-volume approximation to the Euler equations for the transonic flow in quasi-one-dimensional nozzles and past two-dimensional airfoils. For the airfoil problem, grid boundary conditions which eliminate grid skewness near the boundary are suggested. The grid equations with properly assigned boundary conditions are solved using a

numerical scheme that is iterative and explicit. The multigrid method is incorporated to facilitate convergence when solving the grid equations. The procedures that involve searching the new neighbors of the adapted grid points and the subsequent interpolating process for defining flow variables at the new cell centers are designed to avoid the introduction of excessive perturbations to the flow calculations.

To speed up the convergence of the flow calculation, a new four stage coefficient set used in the Runge-Kutta scheme is derived, based upon the idea of reducing the growth factor in the high wavenumber region of the error spectrum. From the results of the test cases, significant improvement in the convergence rate is observed after incorporating the new R-K coefficients to the flow solver.

Transonic flows in quasi-one-dimensional nozzles and over the two-dimensional airfoils are solved on the various solution-adaptive-grids to demonstrate the applicability of the proposed directional-concentration functional and the grid adaptation process from the standpoint of improving the solution accuracy and demonstrating the overall convergence.

ABSTRACT

In order to reduce errors associated with large solution gradients, under the constraint of a fixed number of grid points, it is desirable to have the grid clustered in regions of large gradient, and more widely spaced in regions of small gradient. Such mesh systems cannot be constructed without knowledge of the behaviour of the solution. As a result, the idea of solution adaptive grid generation has been steadily gaining importance in recent years.

The grid equations in this work are formed from a linear combination of the Euler-Lagrange equations derived from functionals measuring smoothness, orthogonality, and concentration. The adaptive grid technique is applied to solve a finite-difference approximation to the full potential equation, for an elliptical cone inclined to a supersonic flow. For this problem, grid boundary conditions which eliminate grid skewness near the boundary are incorporated. The grid equations with properly assigned boundary conditions are solved using a numerical scheme that is iterative and explicit. The multigrid method is incorporated to facilitate convergence.

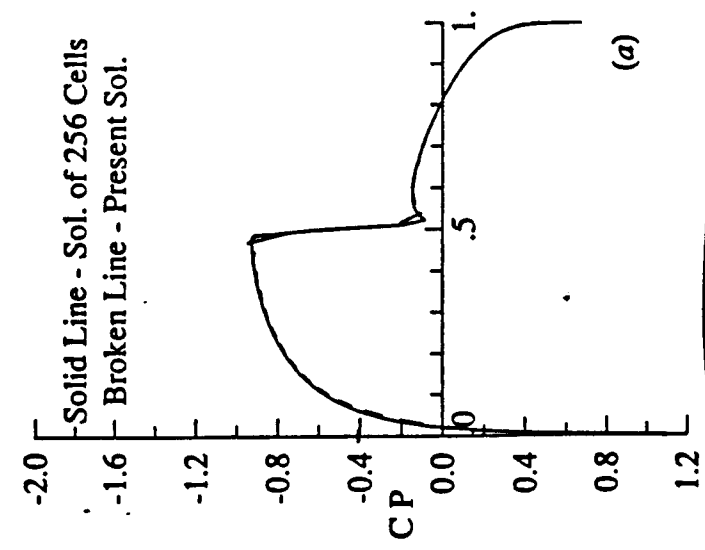
A new scheme for the artificial viscosity in the flow equations, suggested by D. A. Caughey, has also been implemented, and found to remove errors that occurred in the flow solution on highly stretched grids.

DIAGONAL IMPLICIT MULTIGRID SOLUTION OF THE EULER EQUATIONS
FOR TWO-DIMENSIONAL INLETS

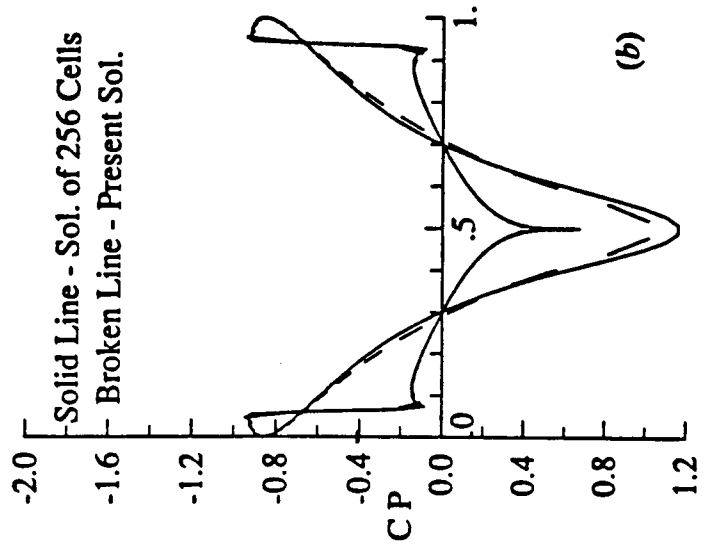
Ravi Kumar Iyer

ABSTRACT

A diagonal implicit multigrid algorithm is developed for the calculation of two-dimensional transonic flow using the Euler equations. Spatial discretization is performed using a finite-volume formulation on a body-fitted mesh. A blended second- and fourth-difference artificial dissipation is added to eliminate odd and even point oscillation and shock overshoots. For computational efficiency, a diagonalization procedure is used, leading to the solution of scalar pentadiagonal systems along each line in each direction. Further convergence acceleration to the steady state solution is achieved by the incorporation of the multigrid method into the algorithm. The scheme is used to compute the flow around a supersonic inlet and a comparison is made with previously published results to demonstrate the increased efficiency of the method.

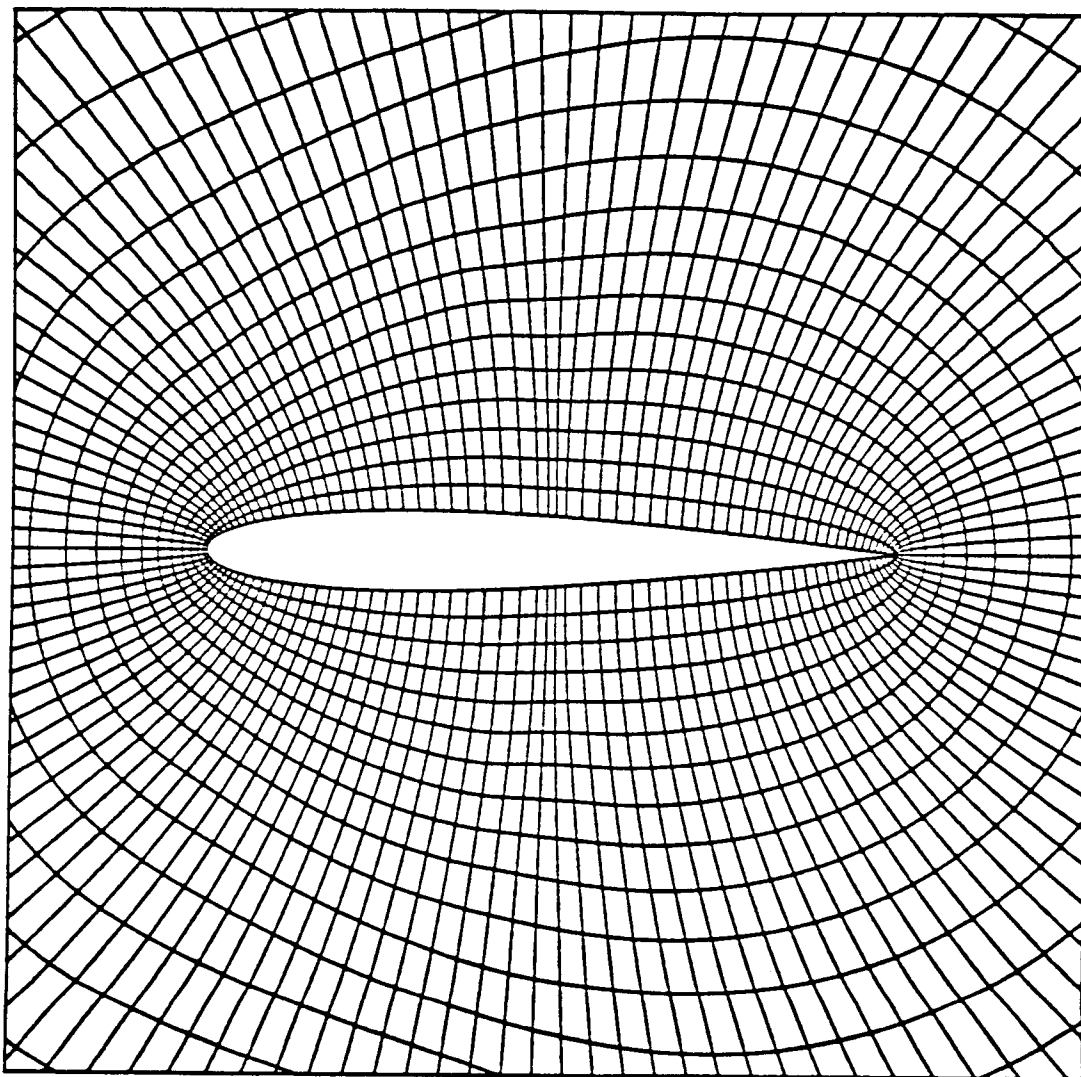


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 Cl 0.0000 Cd 0.0077 Cm 0.0000
 Grid 128x32 Ncyc 499 Res 0.270E-07



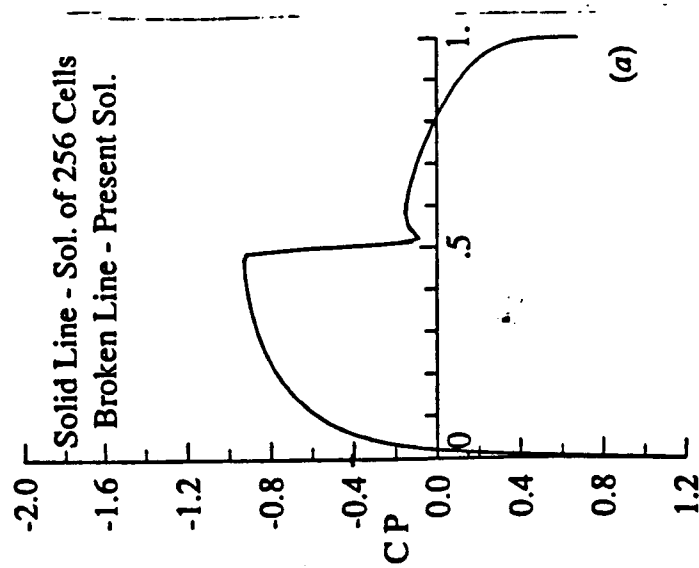
Mach 0.800 Alpha 0.000
 Cl 0.0000 Cd 0.0077 Cm 0.0000
 Grid 128x32 Ncyc 499 Res 0.270E-07

Fig. 1. Lift and drag plots for nonlifting case on smooth grid (dashed line) and on uniform 256 x 64 grid (solid line).

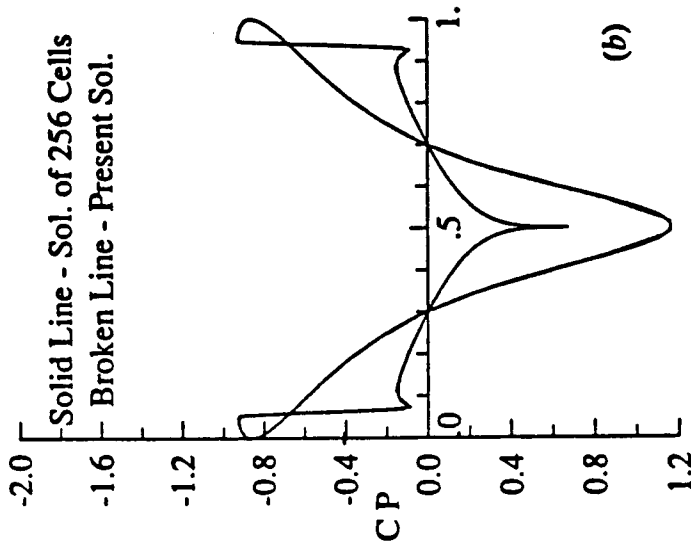


Near airfoil
Grid 128 x 32 Iter= 300
Window size $X1 = 25.2$ $X2 = 26.7$

Fig. 2 . Solution-adapted grid for nonlifting case computed using directional weighting function.

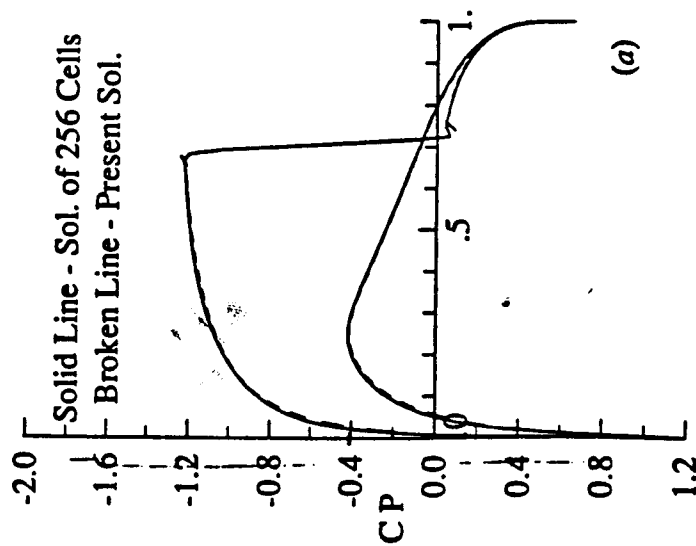


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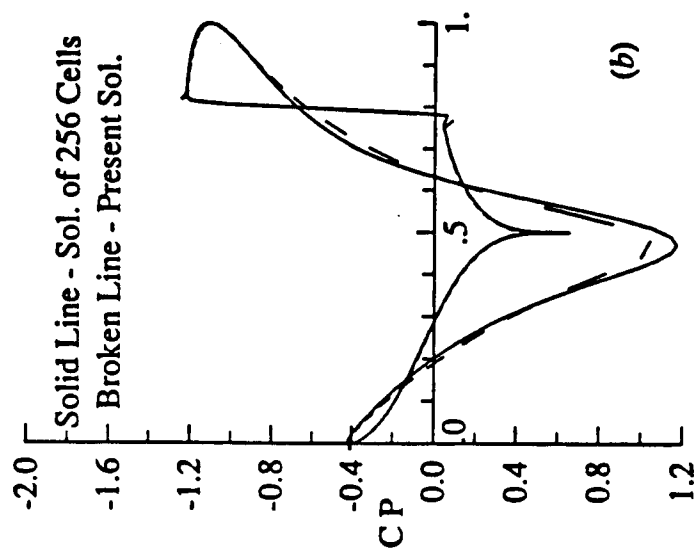


Mach 0.800 Alpha 0.000
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Fig. 3. Lift and drag plots for nonlifting case computed on grid adapted to solution using directional weighting function.

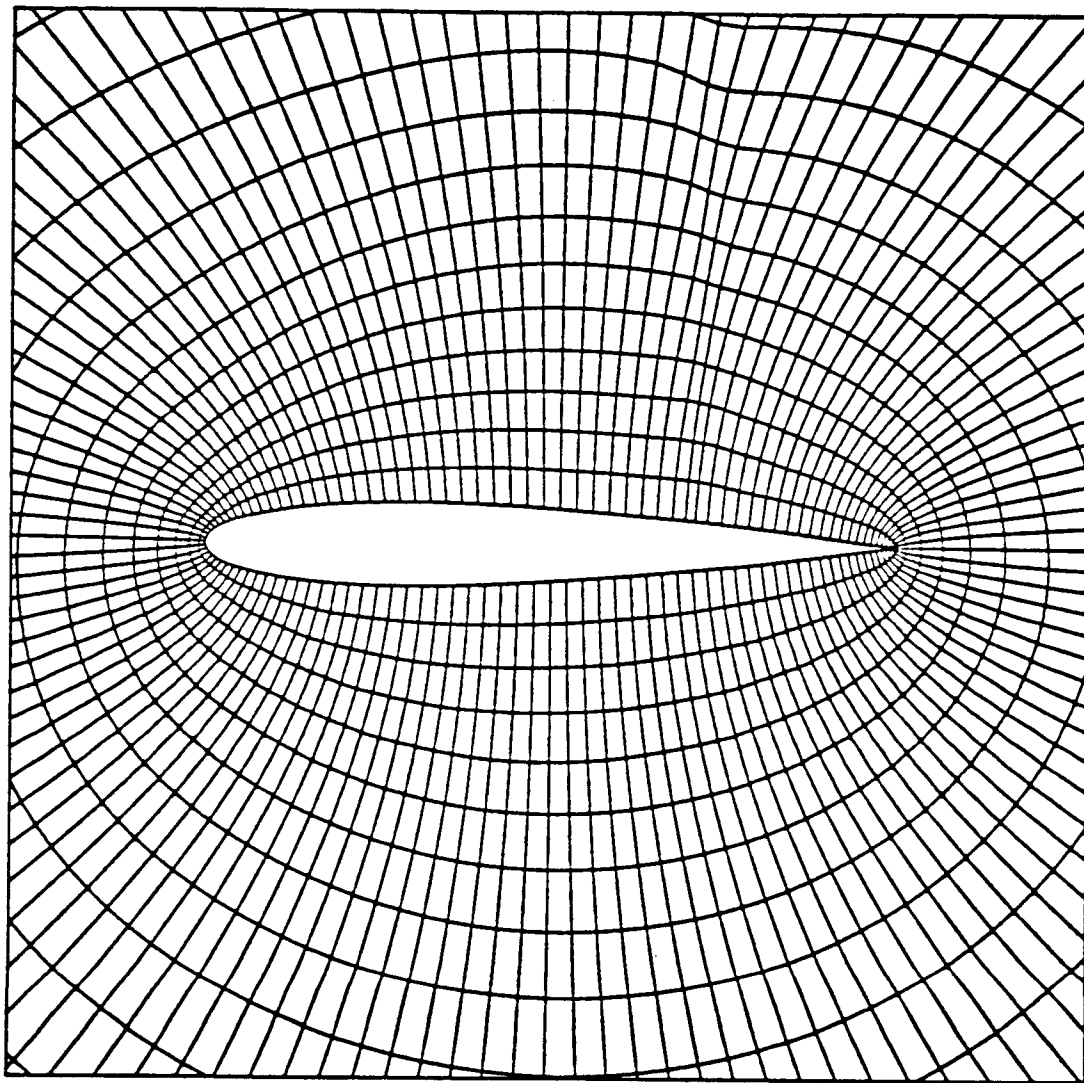


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 Grid 128x32 Ncyc 499 Res 0.124E-07



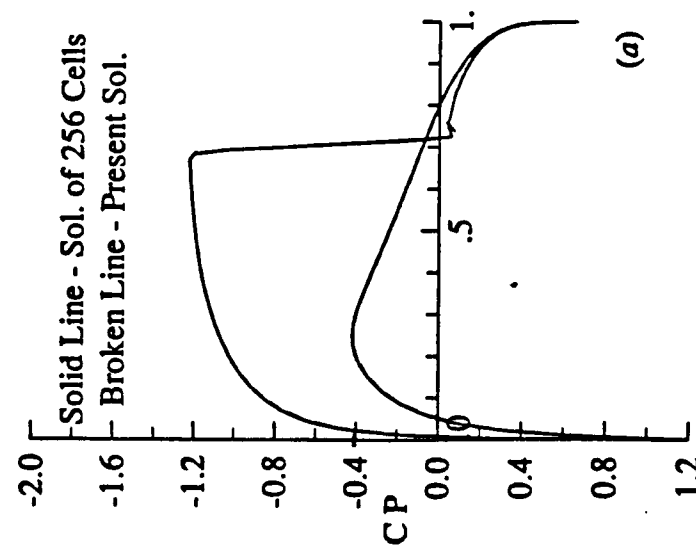
Mach 0.800 Alpha 2.000
 Cl 0.5589 Cd 0.0410 Cm -0.0752
 Grid 128x32 Ncyc 499 Res 0.124E-07

Fig. 4 . Lift and drag plots for lifting Case B on smooth grid (dashed line) and on uniform 256 x 64 mesh (solid line).

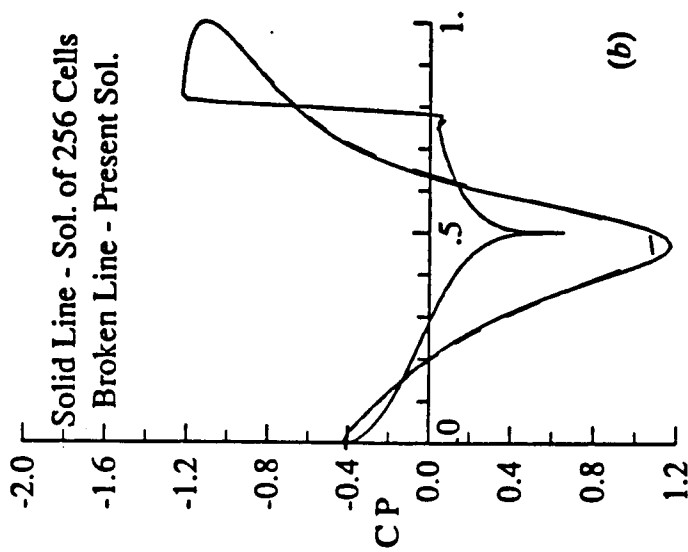


Near airfoil
Grid 128 x 32 Iter= 300
Window size $X1 = 25.2$ $X2 = 26.7$

Fig. 5 . Grid system adapted to lifting Case B using directional weighting function.



Mach 0.800 Alpha 2.000
Cl 0.5612 Cd 0.0422 Cm -0.0755
Grid 128x32 Ncyc 2999 Res 0.909E-06



Mach 0.800 Alpha 2.000
Cl 0.5612 Cd 0.0422 Cm -0.0755
Grid 128x32 Ncyc 2999 Res 0.909E-06

Fig. 6. Lift and drag plots for lifting Case B on grid adapted using directional weighting function (dashed line) and on uniform 256 x 64 mesh (solid line).

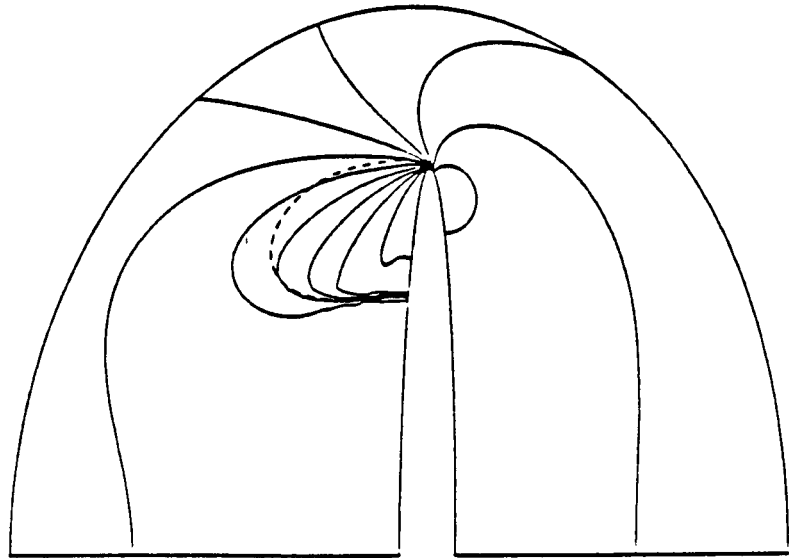


Figure 7.: Detail of pressure contours—on original 128×64 grid.

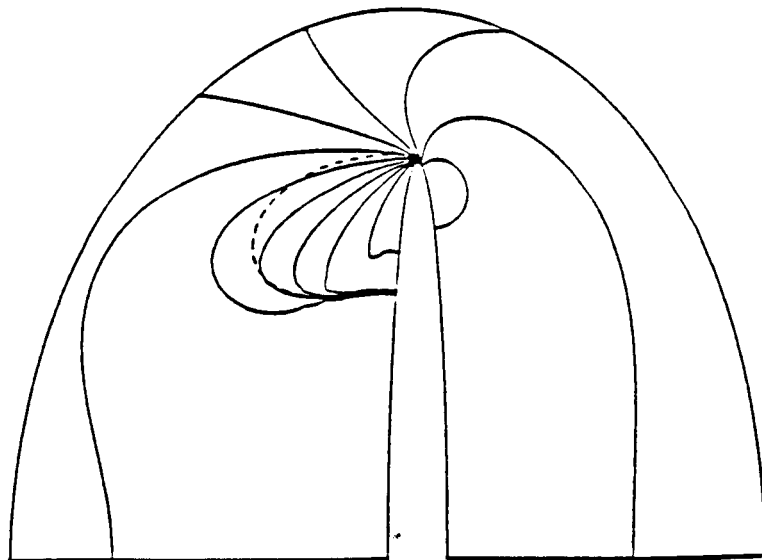


Figure 8.: Detail of pressure contours—on adapted 128×64 grid.

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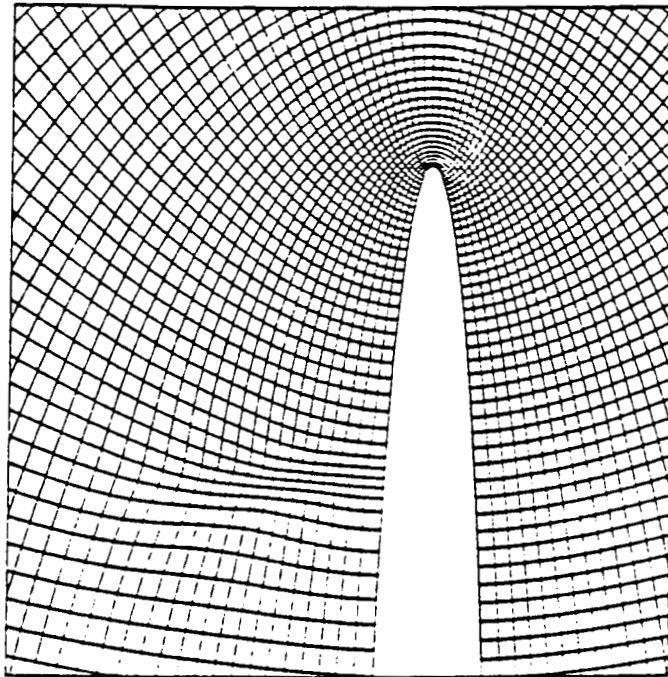


Figure 9. Detail of adapted 128×64 grid—near cross-flow shock.

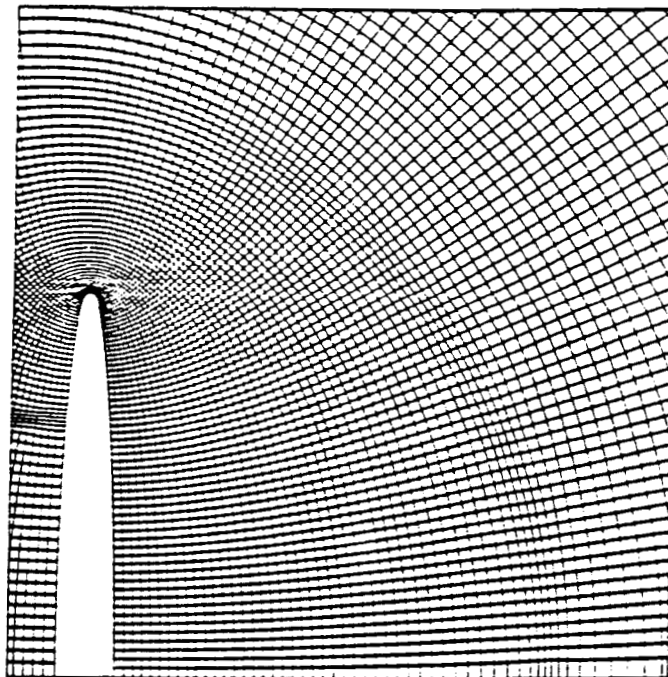
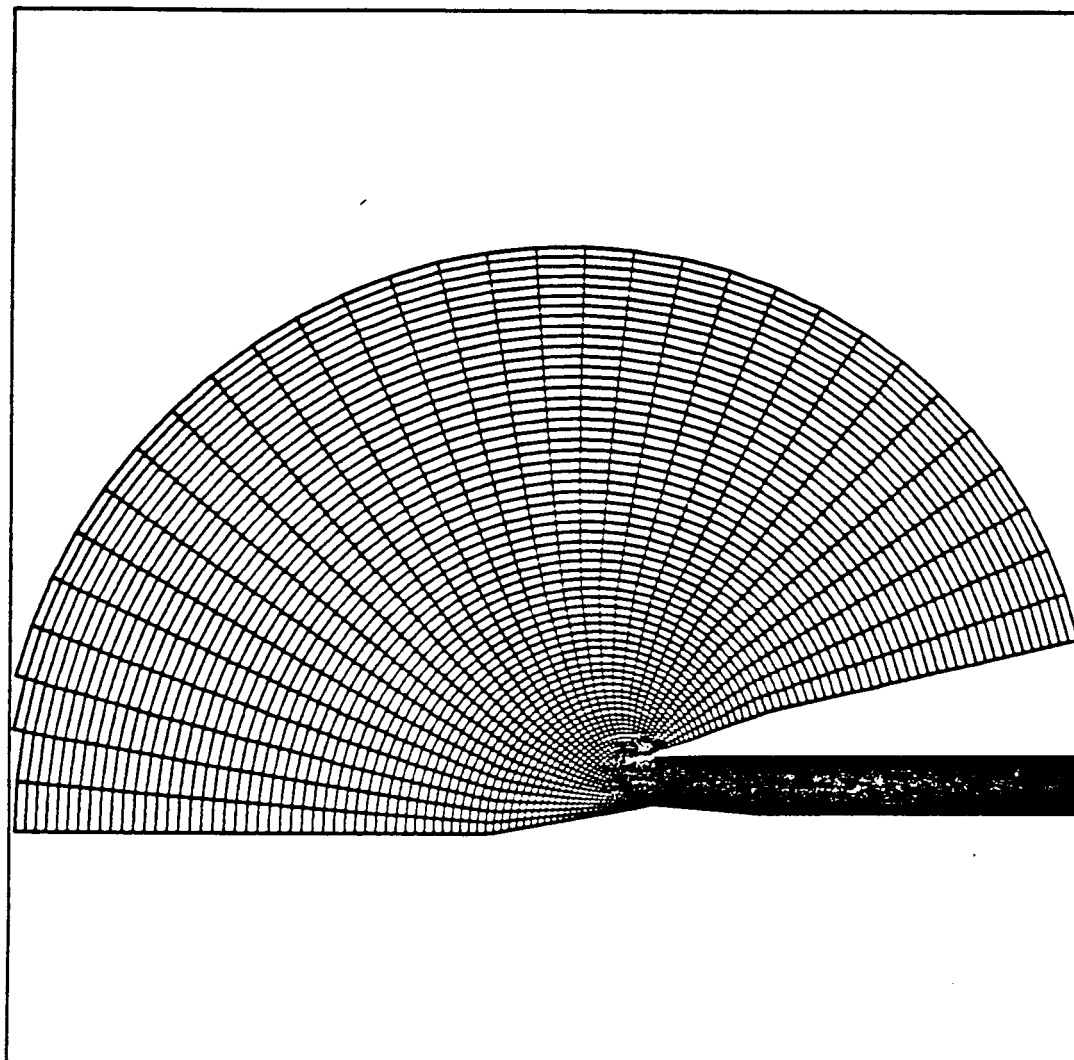


Figure 10: Detail of adapted 128×64 grid—near bow shock.

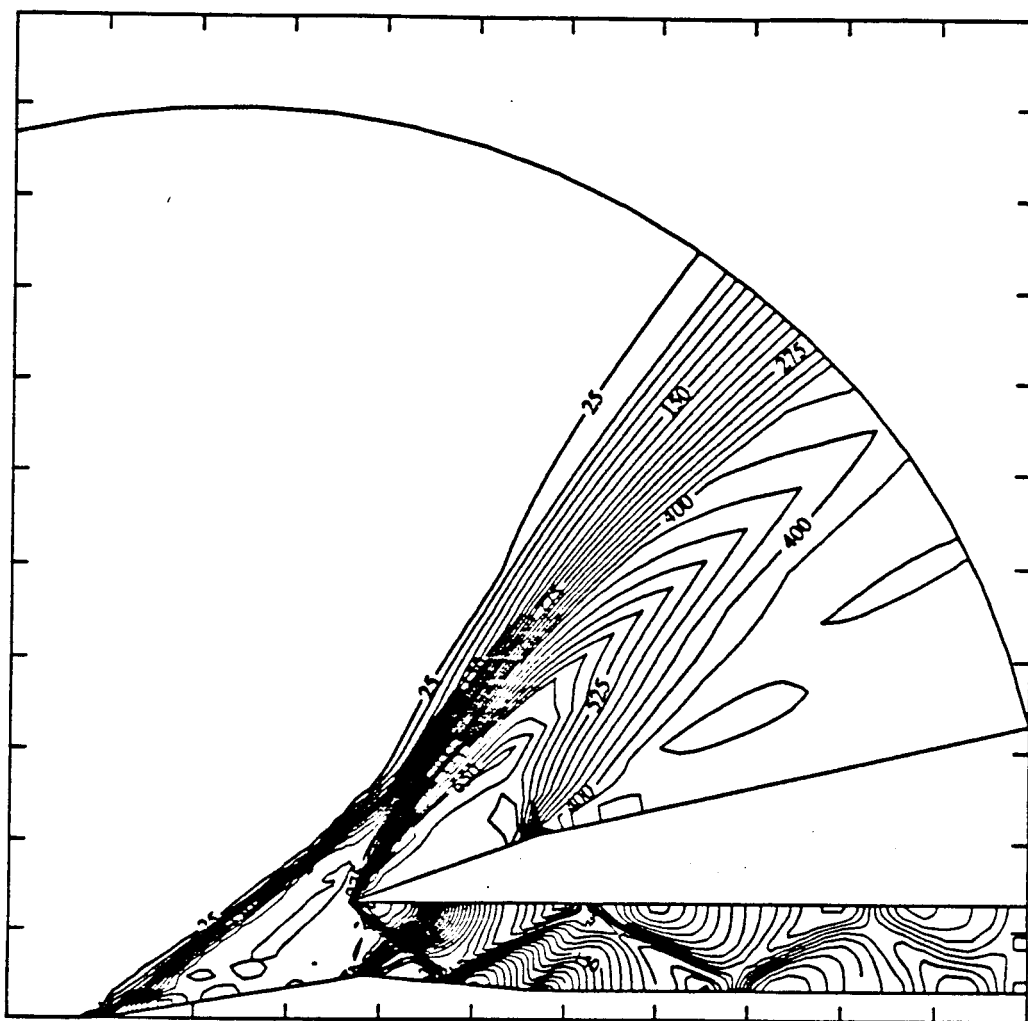
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NASA Inlet

Grid 128 x 32

Figure 11. Grid geometry for NASA two-dimensional inlet.



NASA Inlet

Minimum = $-.2000E+00$

Incrmnt = $0.2500E-01$

Maximum = $0.8000E+00$

Pressure contours

Scale = $0.1000E+04$

Figure 12. Contours of constant pressure for NASA inlet;
free stream Mach number is 2.0.

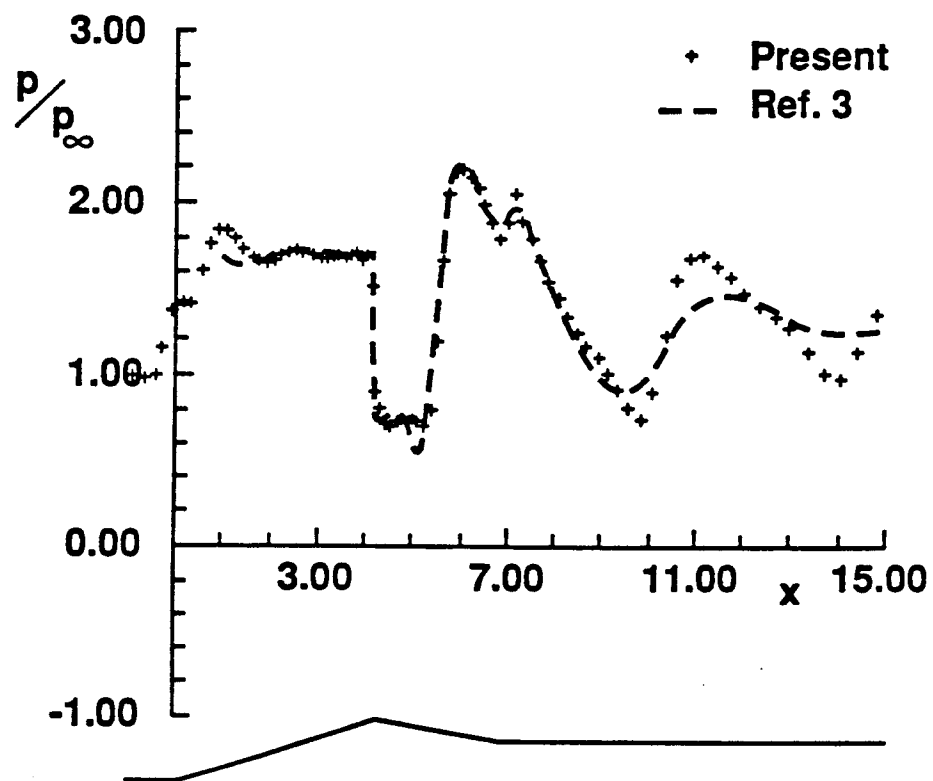
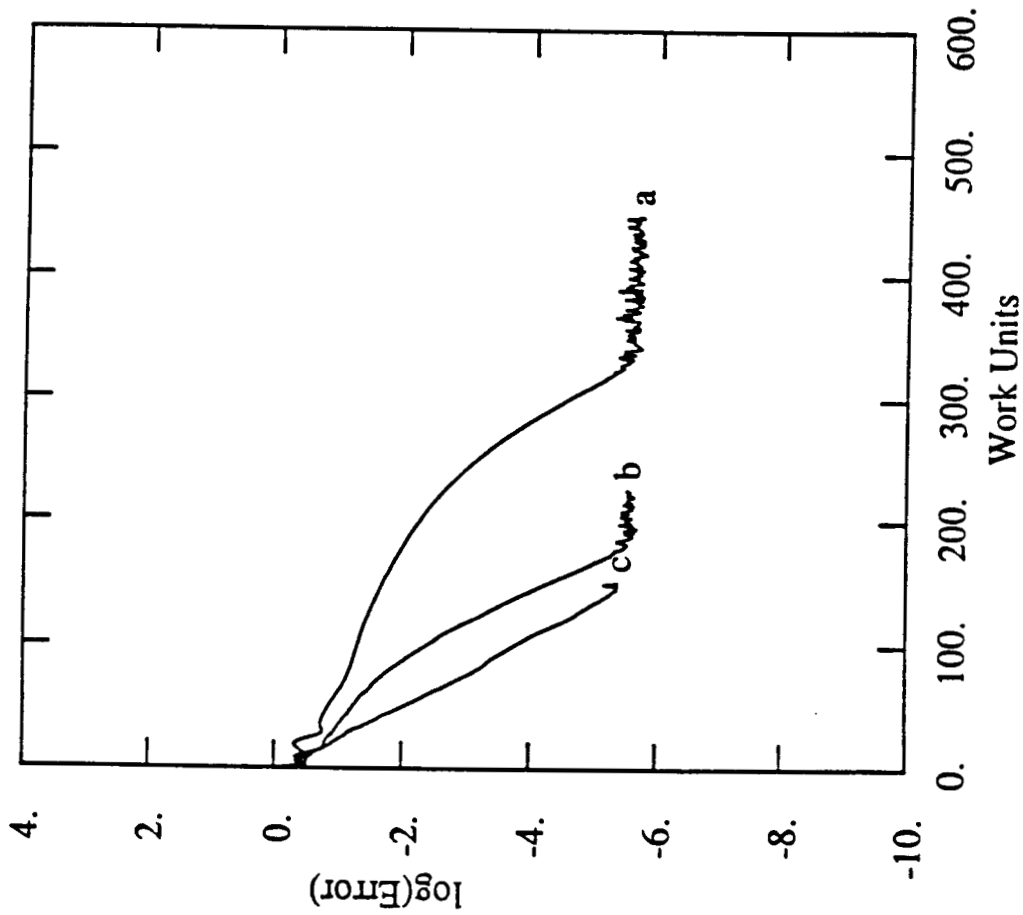


Figure 13. Pressure distribution on centerbody surface of NASA inlet; free stream Mach number is 2.0.

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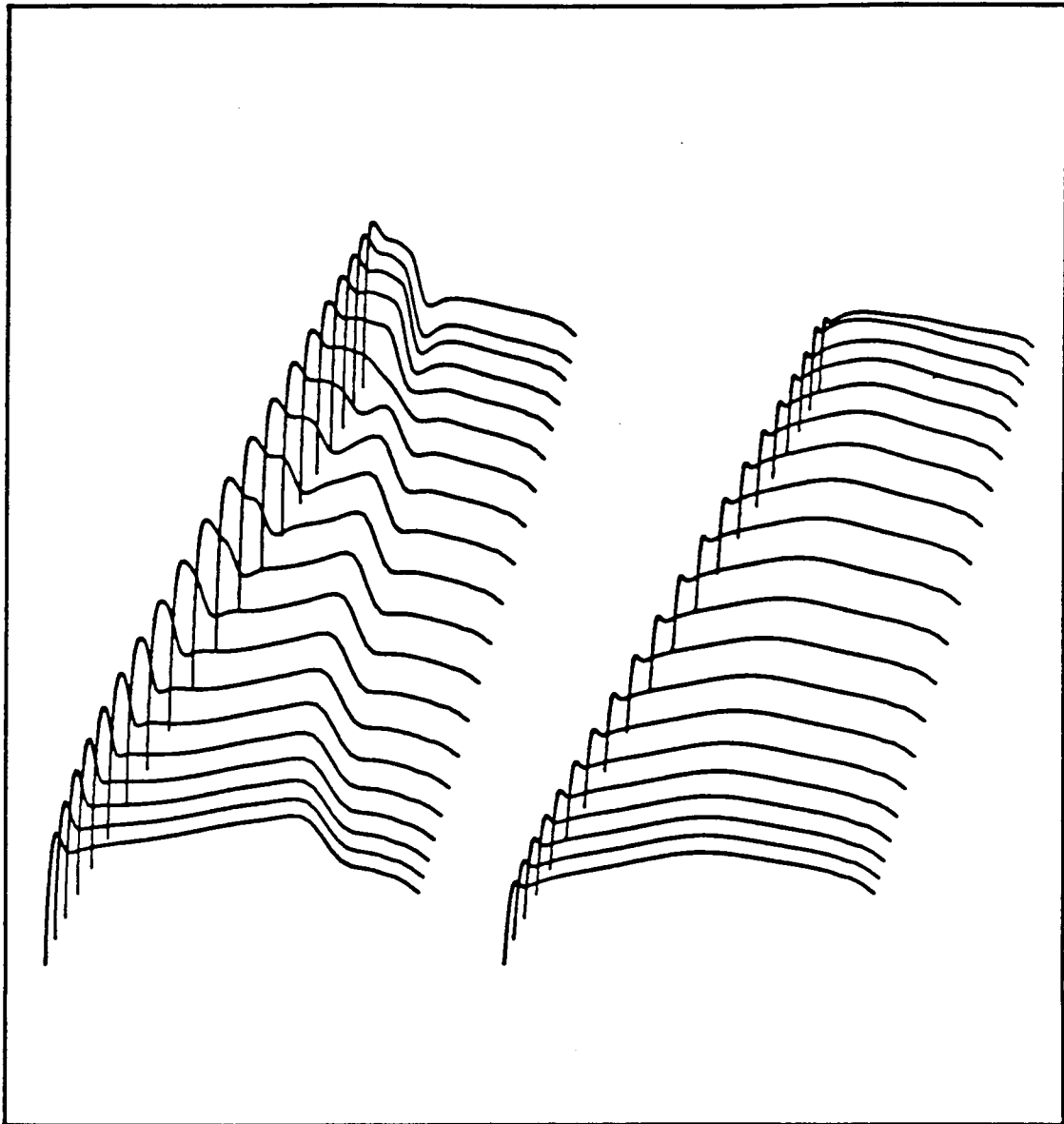
a. Single grid calculation

b. 2-level Multigrid

c. 3-level Multigrid

* Figure 14. Convergence histories for supersonic flow into NASA inlet; free stream Mach number is 2.0.

+



Upper Surface Pressure

Lower Surface Pressure

ONERA WING M6

Mach 0.839

Alpha 3.060

Cl 0.2989

Cd 0.0128

Cm -0.2303

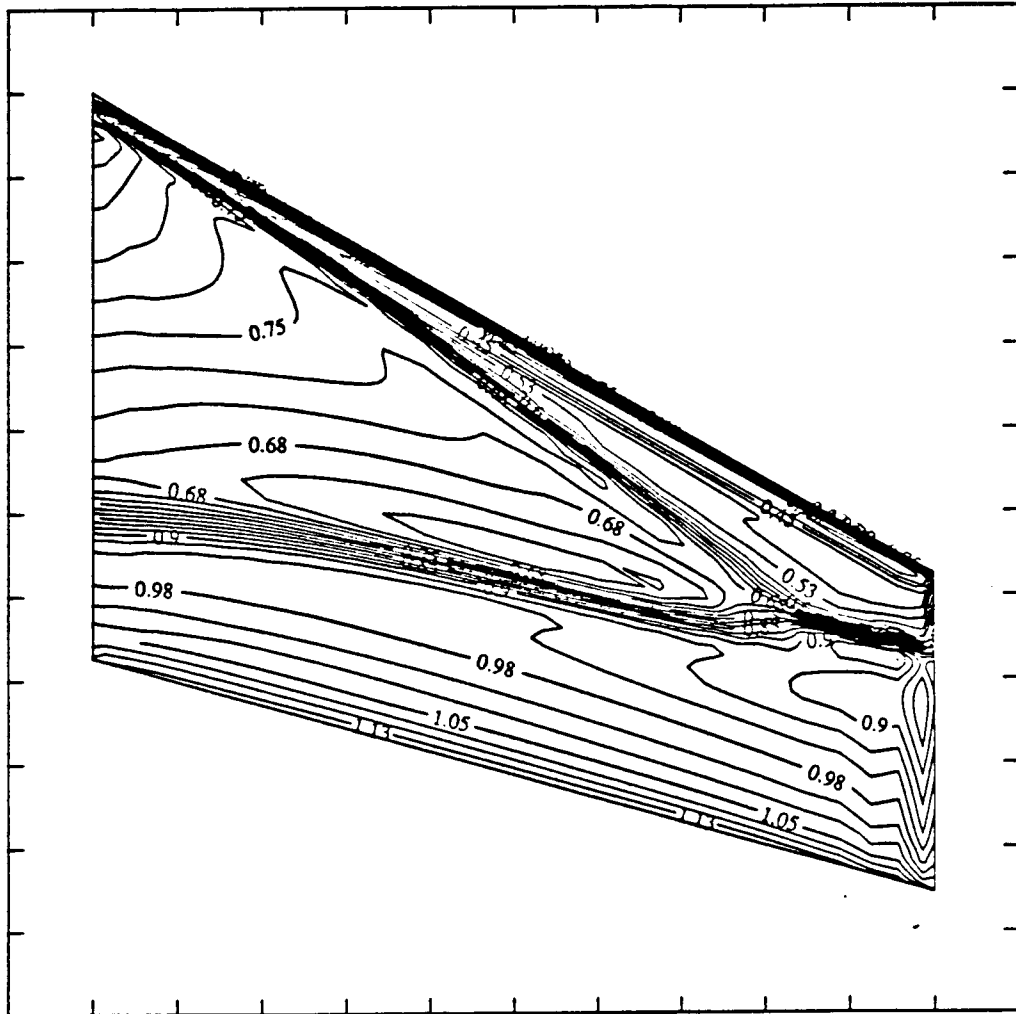
Grid 192x32x32

Work 150.71

Res 0.216E-04

Figure 15. Wing surface pressure distribution for ONERA test case.

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ONERA WING M6

Minimum = 0.2000E+00

Pressure contours

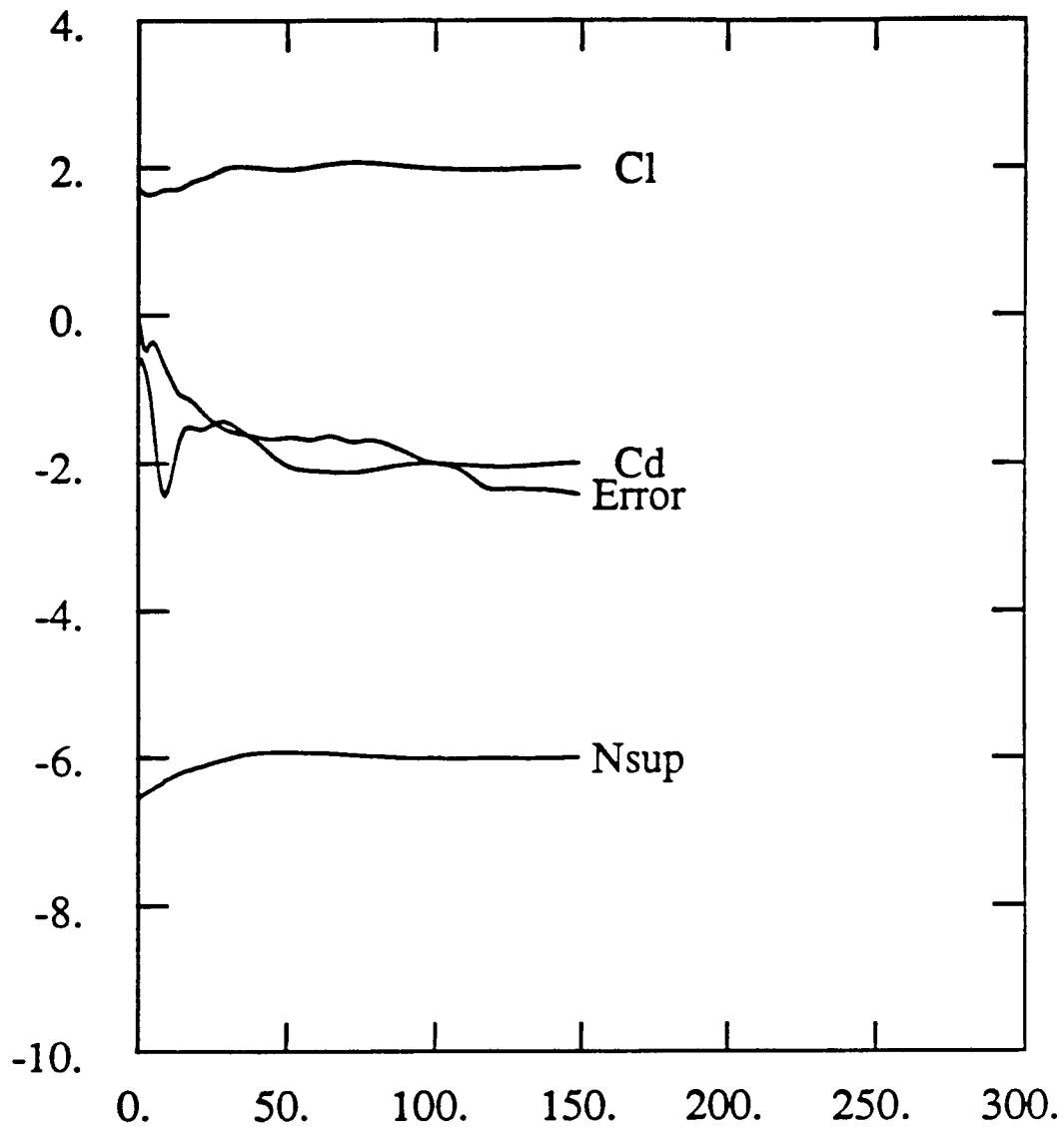
Incrmnt = 0.2500E-01

Maximum = 0.1600E+01

Upper Surface

Scale = 0.1000E+01

Figure 16. Contours of constant pressure on upper surface of ONERA wing M6.



ONERA WING M6(DBL,SINGRID)

Mach 0.839 Alpha 3.060

Res1 0.352E+00

Res2 0.131E-02

Work 149.00

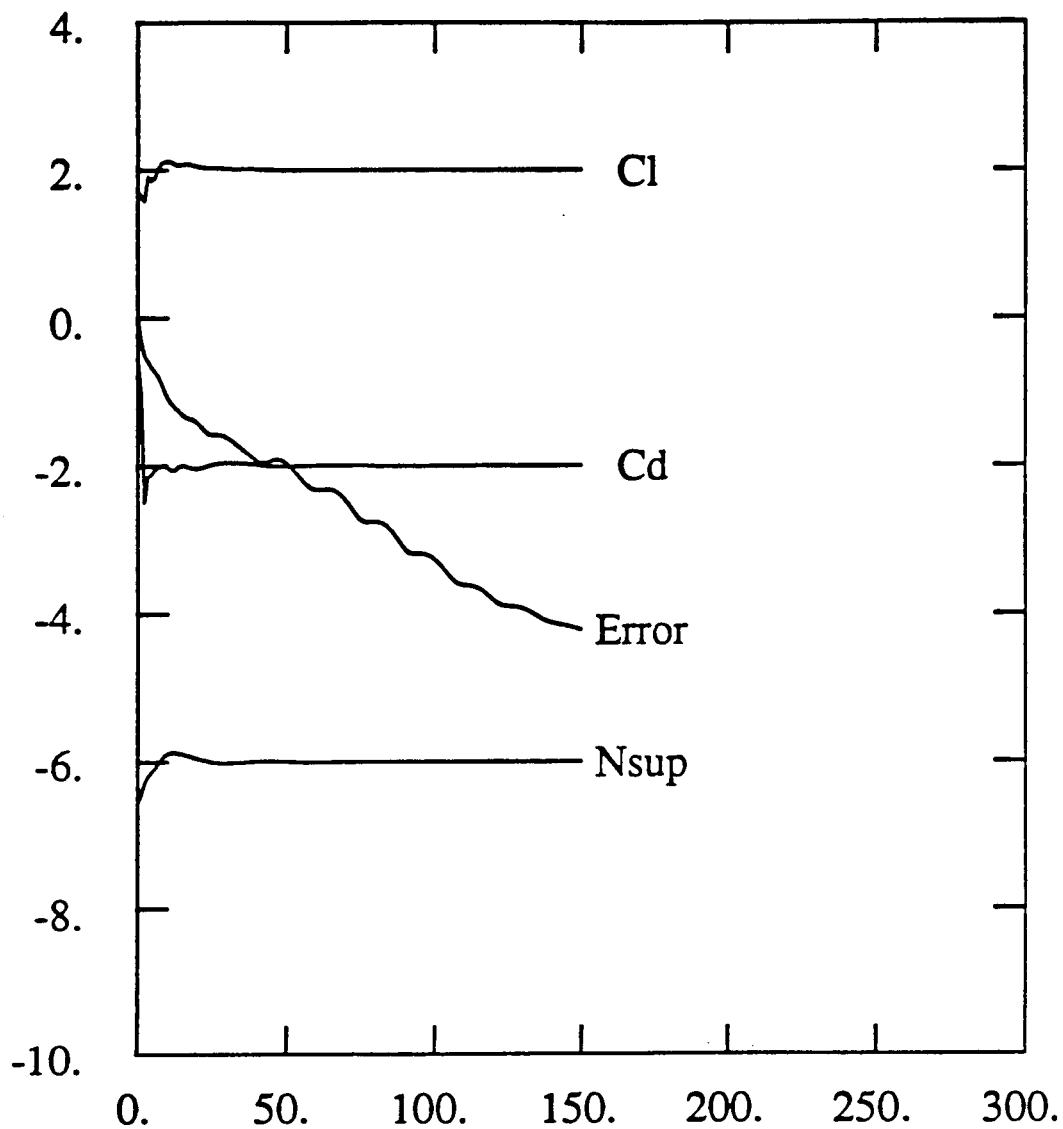
Rate 0.9632

CFL 16.00

Grid 192x32x32

Nmesh 1

Figure 17. Convergence history for ONERA test case; implicit smoothing algorithm without multigrid.



ONERA WING M6

Mach 0.839 Alpha 3.060

Res1 0.352E+00

Res2 0.216E-04

Work 149.71

Rate 0.9373

CFL 16.00

Grid 192x32x32

Nmesh 5

Figure 18. Convergence history for ONERA test case; implicit smoothing algorithm with 5 levels of multigrid.